LOWER HYBRID WAVE ELECTRON HEATING IN THE FAST SOLAR WIND

J. MARTIN LAMING

Naval Research Laboratory, Code 7674L, Washington, DC 20375;
E-mail: jlaming@ssds.nrl.navy.mil

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Abstract. We discuss electron–ion equilibration by lower hybrid waves in the fast solar wind, and its observed effects upon element charge state distributions.

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The solar wind is the plasma medium upon which the various manifestations of solar activity act to cause the phenomena collectively referred to as "Space Weather". It is also an attractive "laboratory" for the more collisionless aspects of plasma physics that can be studied in a variety of ways; by *in situ* measurements of particles, wave activity and fields, and by remotely sensed imaging and spectroscopy of both the wind itself and its source regions in the solar corona. One may study processes in the solar wind, that while potentially important in the search for the solar wind acceleration mechanism, are known now to be crucial in other astrophysical settings. Important examples are the anomalous electron thermal conductivity in cooling flows in clusters of galaxies, and the means by which electrons and ions may (or may not) equilibrate their temperatures in two temperature black hole accretion flows or behind collisionless shock waves in supernova remnants.

The *fast* solar wind is known to emanate from solar coronal holes where the electron temperature is $\sim 8 \times 10^5$ K. At this temperature the ionization balance of Fe is dominated by the Ar-like charge state, Fe^{8+}. However in the fast solar wind observed at 1 AU, Fe is observed to be mainly in charge states Fe^{11+} or Fe^{12+} (Geiss et al., 1995; Ko et al., 1997), requiring the existence of an electron heating mechanism that causes a sufficient increase in electron temperature within about 3 solar radii heliocentric distance to further ionize Fe before charge states freeze in the expanding solar wind. Further, the fact that essentially none of this heat deposited in the electrons seems to conduct back to the coronal hole base also requires an anomalous conductivity.

A recent paper, (Laming, 2004) proposed that electrons in the fast solar could be heated beginning at heliocentric distances 1.5–2.0 solar radii. At these distances ions begin to be strongly heated by resonance with ion cyclotron waves. This causes a dramatic increase in the ion temperature perpendicular to the magnetic field, and a corresponding increase in the ion gyroradii. Under such conditions in a cross-field density gradient of length scale similar to the ion gyroradii (see Figure 1), lower hybrid waves may be excited by the resulting anisotropy in the ion velocity distribution function.[1] These waves damp by heating electrons as well as ions, leading to a collisionless energy transfer from the hot ions to the cooler electrons. Such a scheme bears most relation to an instability previously discussed for two temperature accretion flows by (Begelman and Chiueh, 1988), but similar electron heating mechanisms have also been invoked elsewhere for supernova remnants and cometary X-ray emission (Laming, 2001a,b; Bingham et al., 1997; McClements et al., 1997).

We model the evolution of the ionization balance of the various elements observed in the fast solar wind using an implementation of time-dependent ionization balance within an analytic approximation for the magnetohydrodynamical flow. The new ideas about electron heating have proven a little controversial, despite a long history of study of density inhomogeneities in the solar wind, so we use a code called BLASPHEMER,[2] described at more length in (Laming and Grun, 2002, 2003; Laming and Hwang, 2003; Hwang and Laming, 2003). The electron heating by the lower hybrid instability is implemented by evaluating the ion–electron energy transfer rate in quasi-linear theory, taking this to be two times the wave growth rate times the wave energy density (Karney, 1978). A typical run for the element Fe is shown in Figure 2. At low altitudes Fe^{8+} dominates. At distances beyond 1.5 solar radii heliocentric distance, ion cyclotron heating becomes strong, and some of the energy from the ion heating is able to find its way to the electrons by the instability discussed above. The result is an increase in the average charge state of Fe, consistent with observations, which occurs out to be about 3 solar radii, where charge states freeze in (i.e. the solar wind expansion rate is faster than typical ionization and recombination rates). Results for other elements (C, O, Mg, and Si) show similar behavior (Laming, 2004).

The anomalous thermal conductivity associated with lower hybrid turbulence at the level predicted (Karney, 1978) is also sufficient to inhibit electron heat

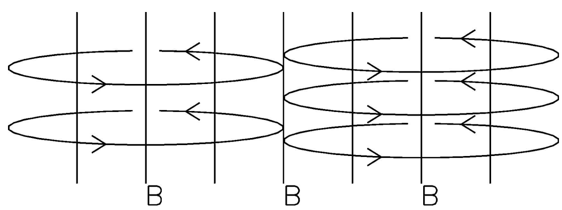

Figure 1. Schematic diagram of lower hybrid wave generation in the density gradient by gyrating ions. The density increases from left to right. In the center of the figure, more ions are moving out of the page than into it, leading to a two-stream instability.

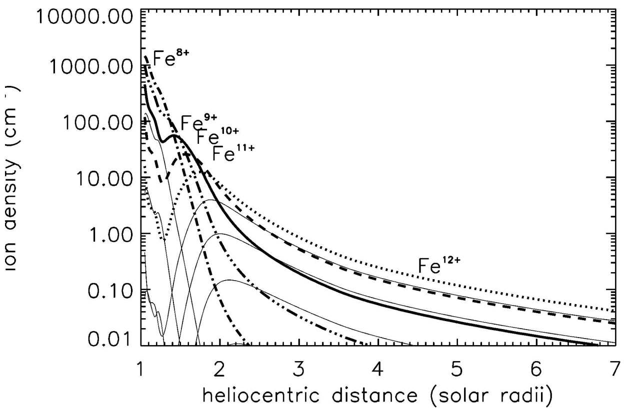

Figure 2. Evolution of Fe ionization balance with heliocentric distance.

conduction back to the sun to the degree required. It is likely that this estimate is in fact an underestimate of the turbulence level, and so similar electron heating could be maintained with lower growth rates for the lower hybrid waves, which are probably consistent with the density inhomogeneities observed in the fast solar wind by interplanetary scintillation. Thus several aspects of the microphysics of collisionless electron–ion equilibration of wide importance elsewhere in astrophysics may be studied by careful observation and modeling of the solar wind. The anomalous conductivity also places constraints on mechanisms by which the ion cyclotron wave necessary for the solar wind acceleration may be excited. To date we have only considered spatial inhomogeneities in solar wind plasmas. Temporal inhomogeneities such as recently invoked for the generation of ion cyclotron waves (Markovskii and Hollweg, 2004) may also play a role, which will be interesting and fun to explore.

Acknowledgments

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Notes

1. Lower hybrid waves are an electrostatic oscillation of the ions, with wavevector close to the perpendicular to the magnetic field, and with wavelength $\gg$ electron gyroradius. Under these conditions, the electrons are pinned on magnetic field lines and may only damp the wave by motions along the magnetic field direction.
2. BLASt Propagation in Highly EMitting EnviRonment.

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